



## Four-wave mixing in InAlGaAs quantum dots

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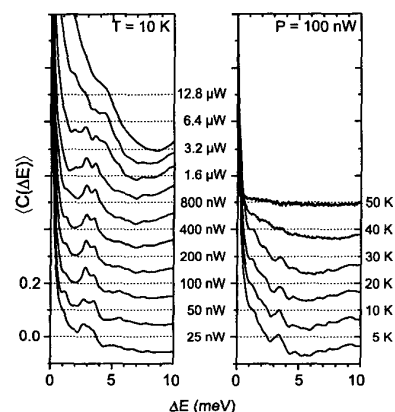
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**QMJ4** Fig. 2. Left hand side: Averaged auto-correlations  $\langle C(\Delta E) \rangle$  at the same sample position with excitation intensity as parameter. The overall shape of the correlation feature remains unchanged over more than two orders of magnitude. Right hand side: Variation of the sample temperature, excitation intensity is constant. The correlation feature vanishes with raising temperature due to the homogeneous broadening of the individual lines. The different averaged autocorrelations are shifted vertically due to clarity. The dotted lines mark the zero line.

have some intermediate separation. They cannot be very close together—due to level repulsion—and cannot be too far apart either—due to the finite linewidth.

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#### QMJ5 2:45 pm

##### Four-wave mixing in InAlGaAs quantum dots

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The non-linear optical properties of semiconductor quantum dots are of interest, both fundamentally and for potential device applications.<sup>1</sup> Large optical non-linearities are predicted due to the three dimensional confinement but the small ac-

tive volume of the dots and their large inhomogeneous broadening strongly reduce the interaction with the electromagnetic field. Until now, four-wave mixing (FWM) in III-V quantum dots has only been reported in optical amplifiers at room temperature, where the interaction length is increased by waveguiding in the quantum dot plane.<sup>2</sup>

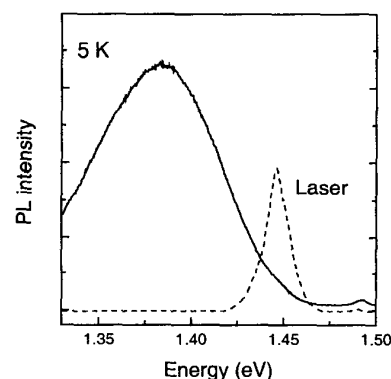
We have carried out degenerate FWM experiments in a slab geometry on a sample containing 10 layers of MBE-grown  $\text{In}_{0.5}\text{Al}_{0.04}\text{Ga}_{0.46}\text{As}$  quantum dots (QDs) with 50-nm  $\text{Al}_{0.08}\text{Ga}_{0.92}\text{As}$  barriers. Ground-state photoluminescence emission from the dots occurs at 1.385 eV with an inhomogeneous broadening (FWHM) close to 80 meV as shown in Fig. 1.

The spectrally integrated FWM signals of the QD sample and a GaAs reference sample measured at 5 K are shown in the inset of Fig. 2. The signals are dominated by strong peaks at  $\tau = 0$  and at multiples of the pulse roundtrip time through the sample. These strong peaks are due to a two-photon transition to the GaAs substrate material<sup>3</sup> and is repeated for each reflection of the excitation pulses. However, the FWM signal due to the dots is clearly visible between the sharp peaks and

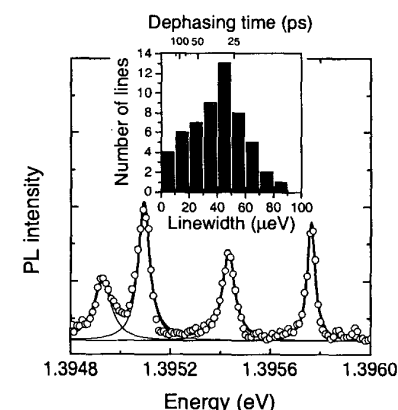
is shown on an expanded scale in Fig. 2. For positive delays, the four-wave mixing signal decays exponentially over more than one order of magnitude with a time constant of about  $11 \pm 1$  ps, corresponding to a dephasing time of  $T_2 = 46 \pm 4$  ps under the assumption of a photon echo. The negative delay signal is caused by FWM due to the reflected probe light and the delayed pump.

The maximum QD FWM signal was observed on the high-energy side of the QD luminescence peak corresponding to the laser spectrum shown as a dashed curve in Fig. 1. The signal intensity reduces to below our detection limit around the center of the PL peak due to the reduced density of dot states. Similar results were obtained for FWM in CdSe/ZnSe islands.<sup>4</sup>

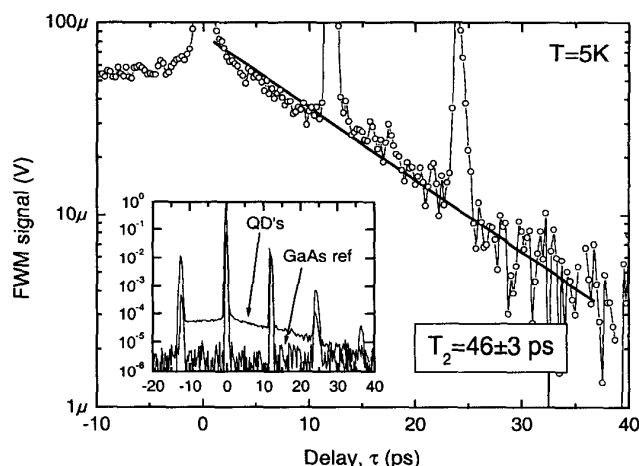
Using microphotoluminescence spectroscopy on a single-layer sample of similarly prepared quantum dots, we have measured the homogeneous linewidth of photoluminescence lines arising from individual dots with a spectral resolution of 20  $\mu$ eV. Fig. 3 shows a Lorentzian fit to four individual PL lines and the statistical distribution of the lines.



**QMJ5** Fig. 1. Luminescence of quantum dots and laser spectrum used in the FWM experiment.



**QMJ5** Fig. 3. Micro-photoluminescence spectrum of individual quantum dots. The inset shows the distribution of linewidths for 60 luminescence lines.



**QMJ5** Fig. 2. Four-wave mixing signal from InAlGaAs quantum dots at 5 K. The inset shows comparison to a reference GaAs sample without dots.

bution of FWHM linewidths of about 60 lines, corrected for the spectrometer response. This distribution of linewidths does not vary with energy across the quantum dot ensemble. The ensemble dephasing time measured in the FWM experiment corresponds to a homogeneous linewidth of  $2\hbar/T_2 = 30 \mu\text{eV}$ , which agrees well with a typical single-dot PL linewidth.

We will also discuss the power and temperature dependence of the QD homogeneous linewidth as well as the dependence of detuning of the FWM signal with respect to the QD luminescence peak.

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Fig. 1. Sample figure from B. R. Masters, "Three-dimensional microscopic tomographic imagings of the cataract in a human lens in vivo," *Opt. Express* **3**, 332 (1998), <http://pubs.osa.org/oearchive/source/6294.htm>

QMJ6

3:00 pm

#### Over-1.5- $\mu\text{m}$ emissions at room temperature of InAs quantum dots in strained InGaAs quantum well

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Since it has been predicted that remarkable improvement of the threshold current density and temperature sensitivity will occur if quantum dots (QDs) are used as the active layer of semiconductor lasers,<sup>1</sup> several groups have attempted to fabricate quantum dot lasers. Recently, it has been of great interest that QDs will be also available for band structure engineering of semiconductor lasers and many groups have achieved the room temperature lasing at  $1.3 \mu\text{m}$  using QDs surrounded with strain-reducing layer as the active layer of laser structure.<sup>2–5</sup> In this paper, we reported the over-1.5- $\mu\text{m}$  luminescence at room temperature of InAs QDs in strained InGaAs quantum well (QW) grown by metalorganic chemical vapor deposition (MOCVD).

All samples were grown by low-pressure MOCVD using trimethylindium, trimethylgallium, triethylgallium and tertiarybutylarsine. First, we investigated the optical characteristics of InAs QDs capped by GaAs. InAs QDs were grown on (100) GaAs substrate. The V/III ratio during the growth of InAs QDs was approximately 0.3

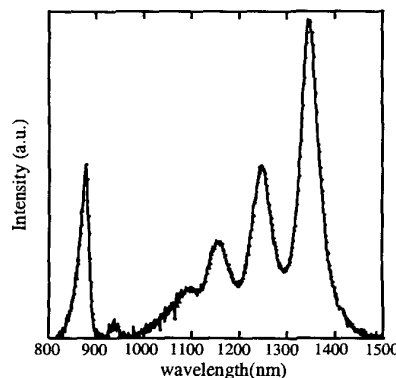
and the growth rate was 0.011 ML/sec. The dot density was  $2.0 \times 10^{10}/\text{cm}^2$  and the mean diameter and height were 25 nm and 5 nm, respectively. After the formation of InAs QDs, GaAs capping layer was grown. The photoluminescence (PL) of the sample were measured using InGaAs cooled-CCD detector. We used a Ti:Sapphire femto-second laser with the peak wavelength of 760 nm as the excitation source. PL spectrum of InAs quantum dots at room temperature was shown in Fig. 1. The excitation power density was  $50 \text{ W}/\text{cm}^2$ . The emissions from the ground and excited states can be observed at 1347 nm, 1248 nm and 1159 nm, respectively. We also observed the very weak emission from the wetting layer at 937 nm.

Secondly, we studied the PL spectrum of InAs QDs in strained InGaAs QW. After the formation of InAs QDs, a 5 nm strained InGaAs QW was grown, and capped by GaAs. The cross-sectional scanning tunneling microscope (SEM) image of this sample is shown in Fig. 2(a). The diameter and height of InAs QDs were 20 nm and 5 nm, respectively. We investigated the PL peak wavelength by changing the indium composition of strained InGaAs QW. The excitation power density was  $2.5 \text{ W}/\text{cm}^2$ . With increasing the indium composition of strained InGaAs QW, the peak wavelength of InAs QDs shifts towards longer values, and we can observe  $1.52 \mu\text{m}$  emissions from InAs QDs in  $\text{In}_{0.45}\text{Ga}_{0.55}\text{As}$  QW (Fig. 2(b)).

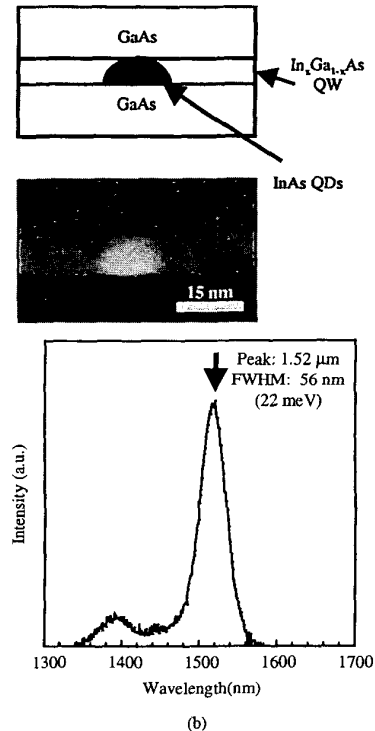
In summary, we have successfully observed over-1.5- $\mu\text{m}$  emissions at room temperature of InAs QDs grown by MOCVD. By capping InAs QDs with strained InGaAs QW instead of GaAs, the PL peak wavelength shifts towards longer value, and we have achieved  $1.52 \mu\text{m}$  emissions of InAs QDs in  $\text{In}_{0.45}\text{Ga}_{0.55}\text{As}$  QW.

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QMJ6 Fig. 1. PL spectrum of InAs QDs capped by GaAs



QMJ6 Fig. 2. (a) Cross-sectional SEM image of InAs QDs in strained InGaAs QW and (b) PL spectrum of InAs QDs in  $\text{In}_{0.45}\text{Ga}_{0.55}\text{As}$  QW.

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